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Effects of Environmental Nuclear Radiation on Optical Fibers

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A comparison of the available data on environmental radiation and on the radiation damage in fibers and glasses under controlled laboratory conditions leads us to the conclusion that long-term exposure to gamma rays and neutrons in the environment does not pose a serious problem for the optical fibers.

Resistance of optical fibers to damage from long-term exposure to environmental nuclear radiation is an important factor to be considered when planning a communication system using these fibers. In this report, we first summarize the nature and intensity of the natural environmental radiation to which the fibers will be exposed, and then discuss the available data on radiation damage in optical fibers and glasses under controlled laboratory conditions. A comparison of these data leads us to conclude that long-term exposure to gamma rays and neutrons in the natural environment does not pose a serious problem for the optical fibers.

I. NATURAL ENVIRONMENTAL RADIATION

The total background radiation at sea level is divided approximately equally between extraterrestrial and terrestrial components.[1] The extraterrestrial component results from the secondary radiations induced by cosmic rays, solar radiation, and Van Allen belt radiation. The terrestrial component is due to the radiation from naturally occurring radionuclides in the earth. Gamma rays (γ rays) and neutrons (n) are important constituents of this radiation[2] and we will concentrate on them for the purposes of this report.

1.1 Gamma rays

A number of measurements of the intensity of the environmental radiation as a function of location, altitude, and latitude have been made. According to Hollaender,[3] the worldwide average exposure is approximately 0.5 R/year (R stands for roentgen, a unit of exposure

dose. A brief discussion of units relevant to this report is given in the appendix). More recent studies (e.g., Ref. 4) indicate that values range from 0.1 to 0.2 rad/year in normal regions (rad is a unit of absorbed dose—see the appendix). An average value of 0.13 rad/year appears to be generally acceptable[5] for *normal regions.** However, for the purposes of our discussion of radiation damage, we will deliberately overestimate the γ-ray dose and assume a value of 0.5 rad/year.

1.2 Neutrons

Hess et al[6] have measured the extraterrestrial neutron flux as a function of neutron energy and found that the total neutron flux $[\int_0^\infty \phi(E)dE]$ at sea level is $\approx 1.5 \times 10^6$ n/cm^2-year.† Measurements by Herbst[8] indicate that the additional neutron flux from terrestrial sources is $\lesssim 10^6$ n/cm^2-year in open air. However, in tunnels or above rocks containing a high density of radioactive nuclides, or in regions with high radioactivity, Herbst obtained a flux of up to 4×10^7 n/cm^2-year. For the purposes of estimating neutron-induced damage, we will assume a rather high value of 1×10^8 n/cm^2-year to provide us with an extra margin of safety.

II. RADIATION DAMAGE IN FIBERS AND GLASSES

2.1 Gamma rays

The γ rays interact with glasses principally by forcing the electrons to leave their normal positions and move through the glass network. The primary consequence of this is an increase in the absorption coefficient in the UV-visible-near-IR range. A detailed study of γ-induced damage in fibers has been made by G. H. Sigel and coworkers[9] at the Naval Research Laboratory. They find that the γ-induced change in the refractive index is small ($<10^{-3}$) at doses as high as 10^9 rads. They also find that the γ-induced losses in optical fibers depend strongly on the fiber composition and vary from 10^{-4} dB/km-rad for bulk Suprasil SiO_2 to 5 dB/km-rad for Corning fiber No. 5010 at 8000 Å. Thus, pure fused silica is extremely resistant to radiation, while the Corning 5010 is quite susceptible to it.

A 20-year exposure to natural environmental γ radiation (assumed to be 0.5 rad/year) would lead to an increase of 50 dB/km for Corning

* There are regions with exceptionally high level of natural background radiation. In some special areas such as Kerala in India or the Santo Spirito province in Brazil, values of up to 14 R/year have been reported (Ref. 2). Certain regions of the Black Forest (Germany) have shown dose rates up to 1.8 R/year. However, these regions are rare and will not concern us in this report.

† Later reports (see Ref. 7) indicate that the values reported by Hess et al may be too high by a factor of 2 to 4.

5010 fiber. However, even in this case, the normal bleaching of the damage[9] would probably reduce the total (20-year) loss to $\lesssim 15$ dB/km. Although this number appears large, it is only a small fraction of the loss of 1000 dB/km present in the Corning 5010 fiber before exposure to any radiation. Furthermore, this is the worst case reported by Sigel et al.[9] The γ-induced losses are generally smaller in fibers with smaller initial losses.* For example, the Corning low-loss fiber (type B), having germanium-doped silica core and pure silica cladding, has an initial loss of 10 dB/km and a γ-induced loss of 0.01 dB/km-rad between 8000 Å and 12,000 Å (1.2 μm). Thus, even if we neglect bleaching, the γ-induced loss in 20 years would amount to only 0.1 dB/km. Since fibers with small initial losses are precisely the ones that will be used in communication systems, it seems reasonable to conclude that long-term exposure to environmental γ radiation will not seriously affect the fiber performance.

2.2 Neutrons

Neutrons interact principally with the nuclei rather than electrons in solids. Neutron radiation, therefore, results not only in increased absorption losses but also in structural changes that lead to changes in density, refractive index, rotary power, birefringence, thermal conductivity etc. Since small differences in refractive indices of the core and the cladding are essential to fiber performance, we will pay particular attention to refractive index changes as well as to increased losses caused by n-irradiation.

To our knowledge, the only study of n-induced losses in optical fibers is by Maurer et al.[10] They irradiated high-silica-glass multimode fiber waveguides with 14-MeV neutrons, using doses of as high as 1.4×10^{12} n/cm^2. They concluded that the n-induced loss varies roughly linearly with the total dose and is less than 1.5×10^{-11} (dB/km)/(n/cm^2) in the 8000-Å to 12,000-Å region. This number, which is obtained from the figure given by Maurer et al,[10] is in fact an overestimate of n-induced damage, because we have disregarded the fact that the n-irradiated samples also received a simultaneous dose ≈ 1000 rads of γ radiation. However, even if we assume this to be the true value, a 20-year exposure to environmental n-irradiation (2×10^9 n/cm^2) would increase the loss by only about 3×10^{-2} dB/km. It should be emphasized that this extrapolation is only approximately valid because neutrons in the environment have a wide range of energies (from 0.01 eV to 10^{10} eV), whereas the neutrons in the con-

* While there is no evidence that the correlation between low radiation damage and low initial losses is *universally* valid, such a correlation definitely exists in the presently available data.

trolled experiment were monoenergetic (14 MeV). However, even after a *thirtyfold* increase, the n-induced losses would still be less than 1 dB/km. Therefore, it seems reasonable to conclude that absorption losses induced by long-term exposure to environmental n-radiation will not seriously affect fiber performance.

Neutron-induced changes in the refractive index of the fibers can be a potential source of problems. We know of no measurements on fibers which can shed light on this problem. However, an extensive literature exists on the effects of n-irradiation on various forms of silica and other commonly used glasses (a good summary is given in Ref. 11). The refractive index of vitreous silica changes by 0.67 percent under a flux of 2×10^{20} n/cm^2 of thermal (<0.1 eV) neutrons.[12] From the measurement by Primak,[12] we deduce that the rate of increase of the refractive index of vitreous silica is approximately 5×10^{-22} per (n/cm^2) for doses less than 1×10^{19} n/cm^2. This suggests that the changes in refractive index induced by environmental neutrons (2×10^9 n/cm^2 in twenty years) will be less than 1×10^{-12}, a truly negligible effect when we consider the fact that the difference in the refractive index of the core and the cladding is typically larger than 10^{-3}.

No data are available on the n-induced changes in refractive indices of other glasses. However, density changes have been investigated for many glasses.[11] For vitreous silica,[12] the density increases approximately linearly (10^{-19} percent per n/cm^2) up to 2.5×10^{19} n/cm^2 and then saturates. Other glasses (except borosilicate glasses) are also quite resistant to neutrons and show very few changes up to about 10^{17}–10^{18} n/cm^2.* The borosilicate glasses are more susceptible because boron, like other light elements, has high neutron cross section. However, even these glasses show damage only when flux levels exceed 10^{14} n/cm^2,* which is some five orders of magnitude larger than the accumulated (20 years) flux of $\approx 2 \times 10^9$ n/cm^2 encountered in the environment.

III. CONCLUSIONS

We have summarized the available data on environmental nuclear radiation and also the data on radiation damage in glasses under controlled laboratory conditions. Unfortunately, the laboratory experiments were not performed with the exact γ ray or neutron energy distributions that one encounters in environmental radiation. It is difficult, therefore, to make accurate predictions about the radiation damage in fibers caused by environmental radiation. However, we

* See Table 6.12 in Ref. 10.

have made some approximate estimates from which it is reasonable to conclude that damage induced by environmental γ or neutron radiation should not pose any serious problems to optical fibers so far as their optical loss or refractive index are concerned. More recent experimental works by Evans and Sigel[13] and Mattern et al.[14] do not affect this conclusion.

Some general comments seem to be appropriate in conclusion. Pure fused silica seems to be extremely resistant to radiation damage. It is also useful to remember that the addition of small amounts (0.1 to 0.2 percent) of Cerium[9,11] makes most glasses more resistant to radiation. We have not discussed damage by α particles, but it is appropriate to mention here that α particles have very short ranges in air as well as in most other materials. Therefore, it seems unlikely that α particles will pose any problems for the optical fibers if the fibers are enclosed in a conduit. Finally, the background luminescence induced by environmental ionizing radiation has been considered by Cohen and Lanzerotti[15] and found to be not significant for fiber optic communications systems.

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APPENDIX

Units of Dosimetry

The most useful units in the study of radiation damage in solids are the particle or photon fluxes as a function of their energy. Thus, $\phi(E)dE$, expressing the number of particles/cm^2-sec in the energy range E to $E + dE$, completely specifies the incident radiation field. However, many special units are frequently used in specifying the radiation. Roentgen (R) is a unit of exposure dose used for X rays and γ rays and is defined as follows. Roentgen is that exposure of X or γ radiation which gives a dose of 87.7 ergs/g to air.

A special unit of absorbed dose is called a "rad." One rad = 100 ergs/g.

Unlike the roentgen, the rad is independent of the irradiated material. This means that a given beam of radiation acting for the same time will deliver different doses, expressed in rads, according to whether it is absorbed in air, tissue, or other materials. The rad in Section I refers to air as the reference material. The rad as used here is indirectly a measure of the radiation field rather than the absorbed dose in the sample because it refers to energy absorbed by air rather than the sample under study. Under these conditions, rad and roentgen are

numerically equal within about 20 percent and can be used interchangeably.

In the work reported by Sigel et al.,[9] Si is used as the reference absorbing material. The differences in using air or Si as the reference material are small (less than a factor of two) and are inconsequential for the purposes of this report.

The conversion between rad and n/cm² and photons/cm² as a function of energy are given by H. Stern.[16] (See also the report by J. Moteff.[17]) For example, for 1 MeV γ-ray photons, 1 rad $\approx 2 \times 10^9$ photons/cm². For 1 MeV neutrons, 1 rad $\approx 2.6 \times 10^8$ n/cm². For γ rays with energy E between 0.07 and 2 MeV, 1 rad (air) $\approx 2 \times 10^9/E$ photon/cm². Conversion factors at other energies may be obtained from the above references. See also the American Institute of Physics Handbook.[18]

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